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EFFECTS OF ACCOMMODATION, VERGENCE AND PUPIL DIAMETER ON SIZE ESTIMATION WHEN VIEWING DISPLAYS

FINAL REPORT

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13. ABSTRACT (Maximum 200 words)

The project was designed to explore the suggestion that inappropriate judgments of the size or distance of objects might contribute to flying accidents (e.g. Roscoe, 1993). The hypothesis of particular interest was that such misjudgments could be caused by accommodation-dependent changes in the size of the optical image on the retina of objects having the same angular subtense but lying at different distances, allied to errors in accommodation. Thus an error in accommodation, caused perhaps by the tendency of the accommodation system to revert to its somewhat myopic tonic or resting state (Toates, 1972; Leibowitz and Owens, 1978; McBrien and Millodot, 1987), would cause the retinal image to be larger or smaller than would be the case for a correctly-focused image. A larger image would be interpreted as indicating that the object was nearer than its true distance, while a smaller image would suggest that the object was further away.

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1. INTRODUCTION

The project was designed to explore the suggestion that inappropriate judgements of the size or distance of objects might contribute to flying accidents (e.g. Roscoe, 1993). The hypothesis of particular interest was that such misjudgements could be caused by accommodation-dependent changes in the size of the optical image on the retina of objects having the same angular subtense but lying at different distances, allied to errors in accommodation. Thus an error in accommodation, caused perhaps by the tendency of the accommodation system to revert to its somewhat myopic tonic or resting state (Toates, 1972; Leibowitz and Owens, 1978; McBrien and Millodot, 1987), would cause the retinal image to be larger or smaller than would be the case for a correctly-focused image. A larger image would be interpreted as indicating that the object was nearer than its true distance, while a smaller image would suggest that the object was further away.

The basic hypothesis outlined above is related to an extensive literature that shows that when an object subtending a fixed angle at the eye is observed, the apparent size diminishes as either the accommodation or convergence is increased (e.g.Wheatstone, 1852; Von Kries, 1924; Grant, 1942; Woodworth and Schlosberg, 1954; McCready, 1965; Komoda and Ono, 1974). When accommodation alone is involved the effect is known as *accommodative micropsia* (e.g. Alexander, 1975; Hollins, 1976).

The current study was carried out in two main phases, each designed to explore a different aspect of the suggested mechanism:

(i) A theoretical study of the validity of various eye models for predicting accommodation-dependent size changes in the retinal image. The basic hypothesis here was that significant shifts in the nodal points of the eye might occur with accommodation to yield substantial changes in the size of the retinal image of any object. Alternatively, the mismatch between the axial positions of the pupil and the nodal points might have similar effects for defocused images.

(ii) A pilot experimental study in which size estimates were made under various experimental conditions with monitoring of the corresponding levels of ocular accommodation. The aim was to determine whether changes in apparent size were in any way related to errors in accommodation or whether other factors played a more important role. Major experimental factors explored were binocularity, pupil size and field-of-view.

2. REVIEW OF THEORETICAL MODELS OF ACCOMMODATION-DEPENDENT CHANGES IN THE SIZE OF THE OPTICAL IMAGE ON THE RETINA

This topic was thoroughly discussed in the Interim Report for the Contract (dated 14th April 1994). We may briefly summarise the Interim Report's conclusions for the following cases:

(i) If an emmetropic eye which is initially viewing a distant object having a particular subtense then accommodates to produce a sharply focused image of a near object having the same angular subtense at the first nodal point, the retinal image of the near object is slightly larger, since the nodal points move forward with accommodation. The size changes are,

however, only of the order of a few percent for near-maximal levels of accommodation of about 8 D (Helmholtz, 1924, p. 392; Pascal, 1952; Le Grand and El Hage, 1980). If the subtenses of the objects are referred to the cornea rather than to the first or anterior nodal point (which in practice cannot normally be unequivocally located for individual eyes) there is a slight reduction by a few percent in the retinal image size for the near object.

(ii) For a spectacle-corrected ametropic eye and sharply-focused retinal images, an additional "proximity factor" associated with the finite vertex distance of the spectacle lenses in front of the eye slightly affects the size changes. Again, however, the size changes involved in changing from distance to near vision are only a few percent, even for the highest prescriptions (Bennett and Rabbetts, 1984, pp.243-244). It is, perhaps, worth emphasising that the conventional "spectacle magnification", involving slight minification with the wear of negative lenses for myopia and magnification for the positive lenses worn by myopes (Bennett and Rabbetts, 1984, pp. 240-241), would affect the retinal images of all objects and hence would not influence the relative sizes of their images.

(iii) If the retinal images are somewhat out-of-focus, as would occur with inappropriate levels of ocular accommodation, size changes in the retinal image are once more expected to be very small. The most thorough discussion of this situation (Smith et al, 1982) reached essentially the same conclusion as earlier authors (Le Grand and El Hage, 1980; Marsh and Temme, 1990). This was that the reduction in retinal image size would only be about 2% for a 10 D error of accommodation when a distant object was viewed. Errors in accommodation thought to be involved with, for example, head-up displays are only about 1 D (Iavecchia et al., 1988), far too small a value to give appreciable changes in the size of the optical image on

the retina.

Overall, then, although there are obviously some limitations in the eye models used, together with variations in the parameters of individual eyes, accommodation-dependent changes in the size of the optical image on the retina seem incapable of explaining the relatively large effects (apparent size changes by factors as high as 2) involved in accommodative micropsia or that have been observed by Roscoe and others in a variety of experimental situations (Roscoe, 1979, 1984, 1985, 1987, 1989; Hull et al., 1982; Norman and Ehrlich, 1986; Iavecchia et al., 1988; Meehan , 1990). It is highly unlikely that refinements in eye models, for example by the inclusion of index gradients or aspheric surfaces (e.g. Navarro et al., 1985), will alter this conclusion.

An alternative explanation must therefore be sought.

3. EXPERIMENTAL STUDY

The basic format of the study involved matching the apparent size of each of a series of "standard" targets with a "comparison" target of similar geometry, the standard and comparison target usually being at different distances.

Targets

The standard targets were white squares or circles on a uniform black background. These

were individually introduced on the line-of-sight of the subject, the physical dimensions of the target being adjusted so that the side length or diameter always subtended 2 degrees at the cornea. The cornea was chosen as reference point in preference to the first nodal point since it can be unambiguously located in any experiment. When lit by ambient room illumination the white targets normally had a luminance of 40 cd/m^2.

The comparison target was a similar white figure on a black background and was generated on the 270 X 200 mm screen of a VDU. The size of the comparison target could be increased or decreased as desired by manipulating the "up" and "down" keys of the computer keyboard. The computer gave the symbol size in arbitrary units. The maximum side length or diameter was 494 units (185 mm) and a single key press changed these dimensions in steps of 2 units (0.75 mm). Calibration with a measuring microscope showed that there was a linear relationship between the dimensions of the symbols and the arbitrary size units output by the computer. It was found, however, that adjustment of the luminance control of the VDU screen affected the size calibration, the size increasing with increased luminance. In all experiments the screen luminance was therefore kept constant at the maximal level (120 cd/m^2) and the calibration appropriate to this level of luminance was always used.

An initial study soon suggested that effects were always very similar with squares and circles. Since the computer program allowed changes in the dimensions of the comparison square to be made more rapidly than those of the circle, it was decided to concentrate on measurements with squares.

Subjects

A small pool of subjects was used for all experiments, although not all subjects were used in every experiment. Major optometric findings are given in Table 1 below. During the studies all subjects wore their optimal refractive correction, if required; those subjects wearing spectacles are shown starred. All achieved 6/6 or better distance vision both monocularly and binocularly.

Table 1: Details of subjects

Subject	LH*	G*	T	S	A	N*	O*	E
Age (Sex)	27(M)	26(M)	25(M)	24(M)	25(M)	25(F)	25(M)	23(F)
Correc-tion	RE -1.75/-1.00 X180 LE -1.75/-0.75 X180	RE -9.25/-0.75X10 LE -8.50/ -1.25 X180	Emm.	Emm.	Emm	RE -1.75 LE -2.25 (CL)	RE -8.00/-1.75X11 LE -9.75/-1.50X171	RE -5.25 LE -3.75/-0.50X5
Acc.Amp. (D)	9	11	9	10	8	9	14	11
Distance 'phoria	2Δexo	Ortho	Ortho	1.5Δ exo	1Δ eso	1Δ eso	3Δ exo	1Δ eso
Near 'phoria	6Δ exo	13Δ exo	9Δ exo	0.5Δ exo	Ortho	4Δ exo	5Δ exo	1Δ exo

Experiment 1: Apparent size as a function of viewing distance

It seemed sensible to first establish the viability of the proposed matching technique and the general magnitude of any apparent size changes. A preliminary trial was therefore carried out with four subjects using binocular viewing.

The VDU comparison target was kept fixed at 2 m (-0.50 D vergence) and the standard targets were viewed at distances of 3, 1, 0.33, and 0.2 m (vergences -0.33, -1.00, -3.00 and -5.00 D respectively), only one standard target being presented at any time. The comparison target was placed as close as possible to the line of sight to each of the standard targets, which were all scaled to subtend 2 degrees at the subject's cornea. Both standard and comparison targets could be seen binocularly on the same horizontal level and their adjacent edges were never more than 2 degrees apart. No restrictions were placed on viewing time and the field of view was also unrestricted, so that the general laboratory environment provided subjects with numerous cues to the distances and relative positions of the various targets.

For each standard target, each subject adjusted the size of the comparison target until the standard and comparison appeared equal in size: the matching procedure was repeated 5 times. All readings were expressed in terms of the corresponding angular subtenses of the comparison target at the cornea. Standard targets were presented in random order.

The results are shown in Table 2.

Table 2: Means and standard deviations of the sidelengths of the square comparison target at 2 m (expressed in degrees subtense at the cornea) required to match 2.00 degree subtense standard targets at the distances indicated. Binocular observation, natural pupils, no restrictions on field-of-view.

	LH	G	T	S	Mean
3m target	2.65±0.033	2.43±0.044	2.86±0.091	2.68±0.083	2.66
1 m target	1.21±0.034	1.36±0.010	1.08±0.053	1.18±0.017	1.21
0.33 m target	1.40±0.035	0.61±0.017	0.64±0.114	0.35±.023	0.75
0.2 m target	1.14±0.051	0.38±0.043	0.40±0.085	0.21±0.021	0.53

The mean results are plotted in Fig.1 in terms of the change in apparent subtense as a function of viewing distance.

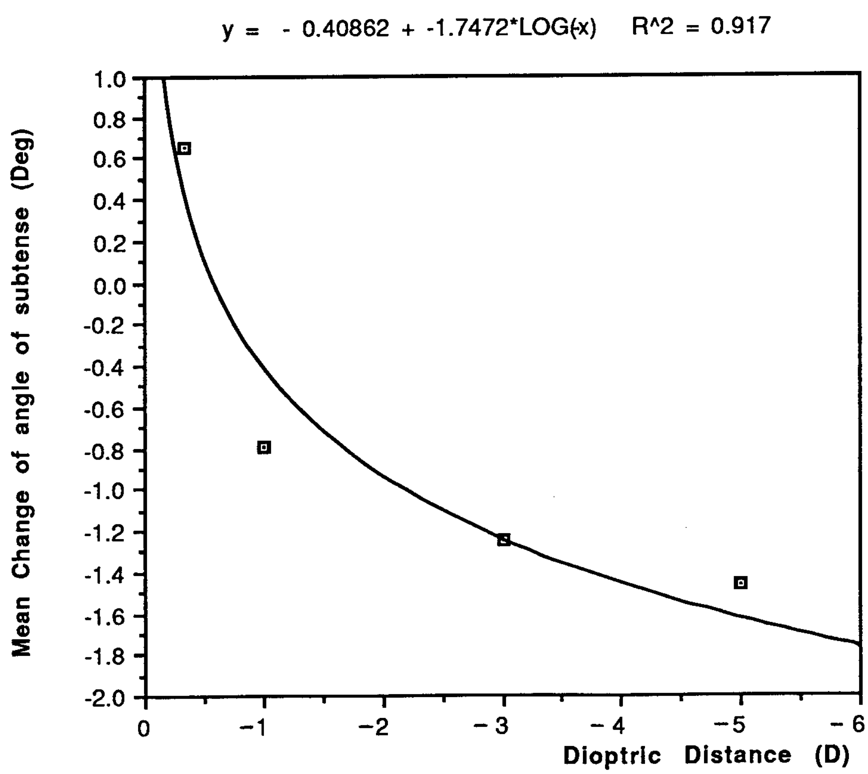

Fig.1. Mean change in apparent size of two-degree square standard targets as a function of target vergence, estimated with a comparison target at 2 m (dioptric distance or vergence -0.5 D). Four subjects; binocular observation; natural pupils; no restriction on field-of-view.

Remembering that the comparison target is at 2.00 m, it is obvious that the standard target which is at the greater distance of 3 m (vergence -0.33 D) tends to be seen larger and that the three nearer standard targets appear substantially smaller. As would be expected, the curve fitted to the points passes through zero size change, corresponding to the target being seen as having its true two-degree subtense, when the vergence of the standard target is close to the -0.5 D vergence (i.e. 2 m distance) of the comparison target. Table 2 shows that there is, however, considerable variation between the results of the different subjects although the data for each individual subject appear reasonably consistent, as indicated by their low standard deviations. There is no evidence that the magnitude of the effects correlates in any way with the refractive corrections of the individual subjects.

It could be argued that the use of the anterior pole of the cornea as a reference point rather than the first nodal point in estimating angular subtenses could cause the reduction in apparent size with viewing distance. However, the first nodal point lies only some 7 mm behind the anterior pole of the cornea, so that even at the closest target distance of 200 mm this factor could only contribute less than 0.07 degrees to any apparent minification. In fact, referred to a nodal point 7 mm behind the cornea the subtenses of the targets at 3, 2, 1, 0.33 and 0.2 m were 1.995, 1.993, 1.986, 1.958 and 1.932 degrees respectively, so that this choice of reference point can only play a very minor role in the results.

Given the existence of a fairly substantial effect linking apparent size with distance, efforts were made to isolate the factors that contributed to its magnitude.

Experiment 2: Effect of a small artificial pupil

In the first experiment it was, of course, necessary for the subjects to change their accommodation during the matching task, since the two targets under comparison were at differing distances. If, however, a small artificial pupil is placed before the eyes their depth-of-focus increases substantially and, as a result, only minor changes in accommodation are elicited by objects at varying distances (Ripps et al., 1962; Hennessy et al., 1975; Ward and Charman, 1985, 1987). Thus errors of accommodation are larger with a small pupil and hence, if errors in accommodation are responsible for the changes in apparent size, one would expect the size changes to be larger than for a larger, natural pupil.

Unfortunately, it is difficult to align artificial pupils during binocular observations, so that a monocular study was carried out in which size matches were made with and without an artificial pupil. The dominant eye was used for the observations.

The artificial pupil used had a diameter of 1 mm. In comparison with the natural pupil diameter of 3-4 mm under the conditions of the experiment, such a pupil leads to a reduction in the light flux reaching the retina. During its use additional lighting was therefore employed to maintain the retinal illuminance at an approximately constant level. Each of 5 subjects completed a total of 10 readings for each of the standard targets: 5 readings being with the natural pupil and 5 with the artificial pupil. The artificial pupil was placed as close to the eye as possible i.e. approximately in the spectacle plane. The VDU comparison target

remained at a constant distance of 2m.

Results for the apparent subtenses in degrees are summarised in Table 3, the first figure representing the result with the natural pupil and the bracketed figure that with the artificial pupil.

Table 3: Subtenses of matching square comparison target at 2m as a function of the distance of the two-degree subtense standard target for 5 subjects viewing the with the natural pupil (unbracketed figures) and with a 1 mm diameter artificial pupil (bracketed figures).

	LH	G	A	S	N	Mean
3 m	2.24(2.16)	1.94(1.83)	2.71(2.68)	2.45(2.35)	2.62(2.56)	2.39(2.32)
1 m	1.71(1.89)	1.97(1.89)	1.53(1.55)	1.40(1.58)	1.73(1.91)	1.67(1.74)
0.33 m	1.50(1.76)	1.55(1.82)	1.28(1.46)	0.98(1.46)	1.04(1.65)	1.27(1.63)
0.20 m	1.23(1.67)	NA	1.07(1.49)	0.87(1.49)	0.78(1.56)	0.99(1.55)

The standard deviations of the results for individual observers were small and very similar to those in Experiment 1: they have therefore been omitted for brevity.

For the natural pupils the changes in apparent size under monocular conditions are slightly smaller than those found under binocular conditions in experiment 1. If the subset of subjects who participated in both experiments 1 and 2 is considered, their binocular and monocular results can be compared in Table 4.

Table 4: Comparison of size estimates of 2 degree, square, standard targets for those subjects who completed experiments 1 and 2. In each case the first, unbracketed figure is the binocular result, the second, bracketed figure the monocular result. Note that the estimated size is always closer to 2 degrees in the monocular case

	LH	G	S	Mean
3m	2.65 (2.24)	2.43(1.94)	2.68(2.45)	2.59(2.21)
1m	1.21(1.71)	1.36(1.97)	1.18(1.40)	1.25(1.69)
0.33m	1.40(1.50)	0.61(1.55)	0.40(0.98)	0.80(1.34)
0.2m	1.14(1.23)	0.38(NA)	0.21(0.87)	0.58(1.05)

This effect cannot be regarded as fully confirmed, however, since the experiments were carried out at different times and few subjects were used. It would not be unreasonable that effects should differ under binocular and monocular conditions, since the effects of convergence are absent under the latter and convergence is known to contribute to the micropsia found with near objects (e.g.Duane, 1900; Heinemann et al., 1959; Alexander, 1975; Hollins, 1976).

The important finding in Table 3, which is clearly visible in Fig.2, is that, although there are inter-subject differences, all individuals follow the same general trend of showing smaller changes in apparent size with the artificial pupil. All the results with the pupil are closer to the "ideal" value of 2 degrees.

It is tempting to ascribe these differences to differences in accommodation although it is also possible that restrictions in the field of view associated with the artificial pupil might also play a role.

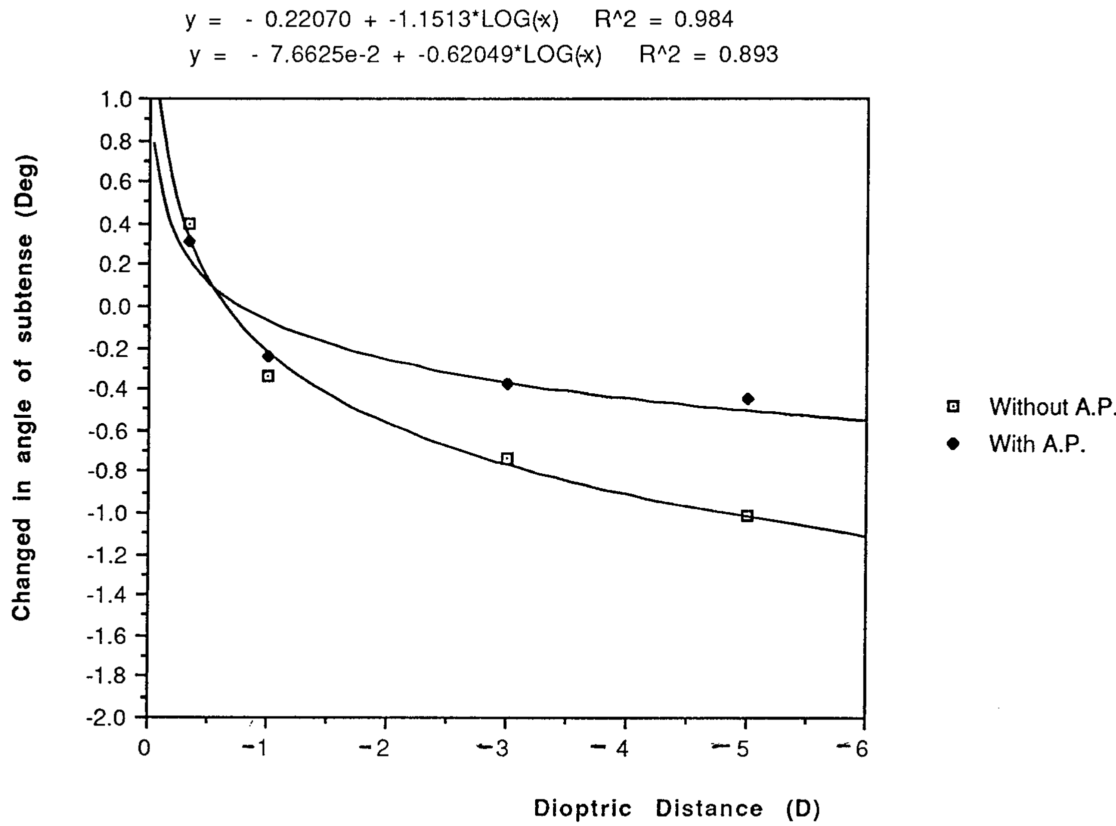

Fig.2. Mean change in apparent size of 2-degree standard targets as a function of target vergence. Five subjects; monocular observation; no restriction on field-of-view. Square symbols: natural pupils. Diamond symbols: 1 mm-diameter artificial pupil.

Experiment 3: Accommodation with and without an artificial pupil

In order to confirm that less accommodation was exercised with the 1 mm artificial pupil, a direct study of the accommodation response as a function of target distance was made. Accommodation was recorded with a Canon R-1 Autorefractor. This instrument has been widely used in accommodation studies and has been shown to have adequate validity and reliability (Matsumura et al., 1983; McBrien and Millodot, 1985). Its great advantage is that the refractive state of the eye can be recorded while targets are viewed without obstruction through a large beamsplitter on the top of the instrument. Since the instrument needs a roughly 3 mm pupil to provide correct measurements, a normal artificial pupil could not be used. Instead the 1 mm-diameter artificial pupil was drilled in Kodak Wratten 87 filter material: this is opaque in the visible but transparent to the infra-red wavelengths used by the autorefractor.

Subjects were positioned on the chinrest of the instrument and viewed the same standard and comparison targets as before. To provide a more complete record of the response/stimulus curve, responses to additional square standard targets subtending 2 degrees at distances of 0.67, 0.5 and 0.25 m were also recorded. At least 10 measurements of accommodation were taken for each target distance and pupil condition.

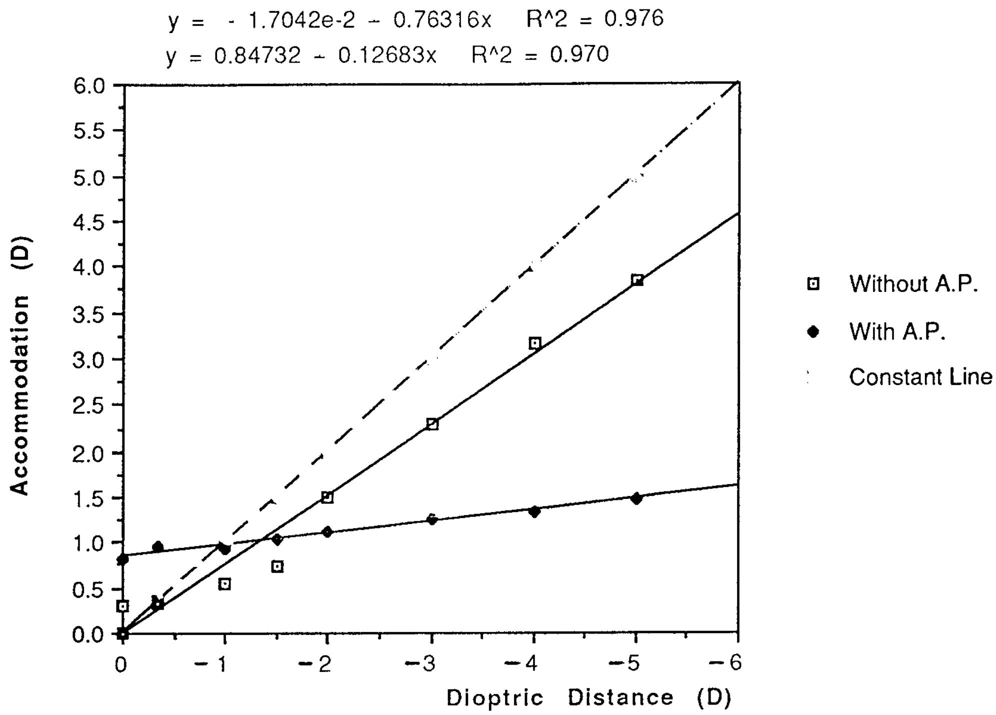

Fig.3. Mean levels of accommodation for when viewing 2-degree square standard targets at the dioptric distances (vergences) indicated. Four subjects; monocular observation; no restriction on field-of-view. Diamond symbols: natural pupils. Square symbols: 1-mm artificial pupil.

The results found are summarised in Table 5 and in fig. 3. It is obvious that, as expected, changes in the level of accommodation with target distance are much smaller with the artificial pupil. With the reduced pupil the level of accommodation remains close to the tonic or resting level which also manifests itself as the dark focus (Hennessy et al., 1976; Ward and Charman, 1985, 1987).

DISTANCE (M) WITHOUT AP	SUBJECT LH ACCM (D)	SUBJECT S ACCM (D)	SUBJECT A ACCM (D)	SUBJECT N ACCM(D)	MEAN ACCM (D)
9	0.25	0.79	0.17	0.05	0.19
3	0.26	0.44	0.16	0.43	0.32
1	0.08	0.65	0.4	0.9	0.51
0.67	0.59	1.14	0.71	1.12	0.89
0.5	1.32	1.6	1.34	1.65	1.48
0.33	1.9	2.42	2.15	2.59	2.27
0.25	2.83	3.39	2.83	3.33	3.1
0.2	3.78	3.91	3.6	4.01	3.83
DISTANCE (M) WITH AP					
9	0.37	1.58	0.6	0.7	0.81
3	0.77	1.61	0.12	1.3	0.95
1	0.52	1.6	0.26	1.28	0.92
0.67	0.75	1.91	0.22	1.31	1.05
0.5	0.8	2.15	0.2	1.32	1.12
0.33	0.4	1.37	1.17	2.11	1.26
0.25	0.78	1.64	1.21	1.69	1.33
0.2	1.07	1.99	0.7	2.16	1.48

Table 5. Monocular, steady-state accommodation responses of 4 subjects to 2-degree square standard targets at the distances indicated Top: natural pupils. Bottom: with 1 mm-diameter artificial pupil.

These findings of experiments 2 and 3 are interesting from several points of view. First, with the smaller pupil, as is evident from figs. 2 and 3, errors in accommodation (focus) are generally larger and yet the errors in size estimation are smaller. On the "inappropriate accommodation" or "zoom lens" hypothesis (Roscoe, 1989, 1993), larger size judgement errors would be expected. On the other hand, if as some authors have suggested the reduction in size is related to the accommodative effort, i.e. to the neural signals that innervate the ciliary body (Lockhead and Wolbarsht, 1989) a smaller size reduction would be expected with the small pupil, as observed.

It might be objected that the failure to observe the larger size judgement errors predicted by the "inappropriate accommodation" hypothesis is in some way associated with the position of the artificial pupil, which was located some 15 mm in front of the eyes rather than in the plane of the natural pupil (Helmholtz, 1924, pp.127-128; Biersdorf and Baird, 1966; Tucker and Charman, 1975; Marsh and Temme, 1990;). As discussed in the Interim Report (pp.8-9), the associated changes in the path of the chief ray for the case of under-accommodation for near objects tend to cause the retinal image to be larger than it would be for the same state of defocus with the natural pupil (see Fig. 4, reproduced from the Interim Report). This would tend to lessen the size reduction in comparison with that observed with the natural pupil. However, with all errors of focus being less than 4 D, we find that the changes in size associated with this effect would always be expected to be less than 10%, whereas, for example, the 0.2 m standard target is seen as being almost twice as large with the small pupil at 15 mm in front of the eye than with the natural pupil (see Table 4). If the pinhole is moved well in front of the eye the effect is, of course, much larger as was found by Biersdorf and Baird (1966) and Hennessy (see Roscoe, 1989 p.50, 1993).

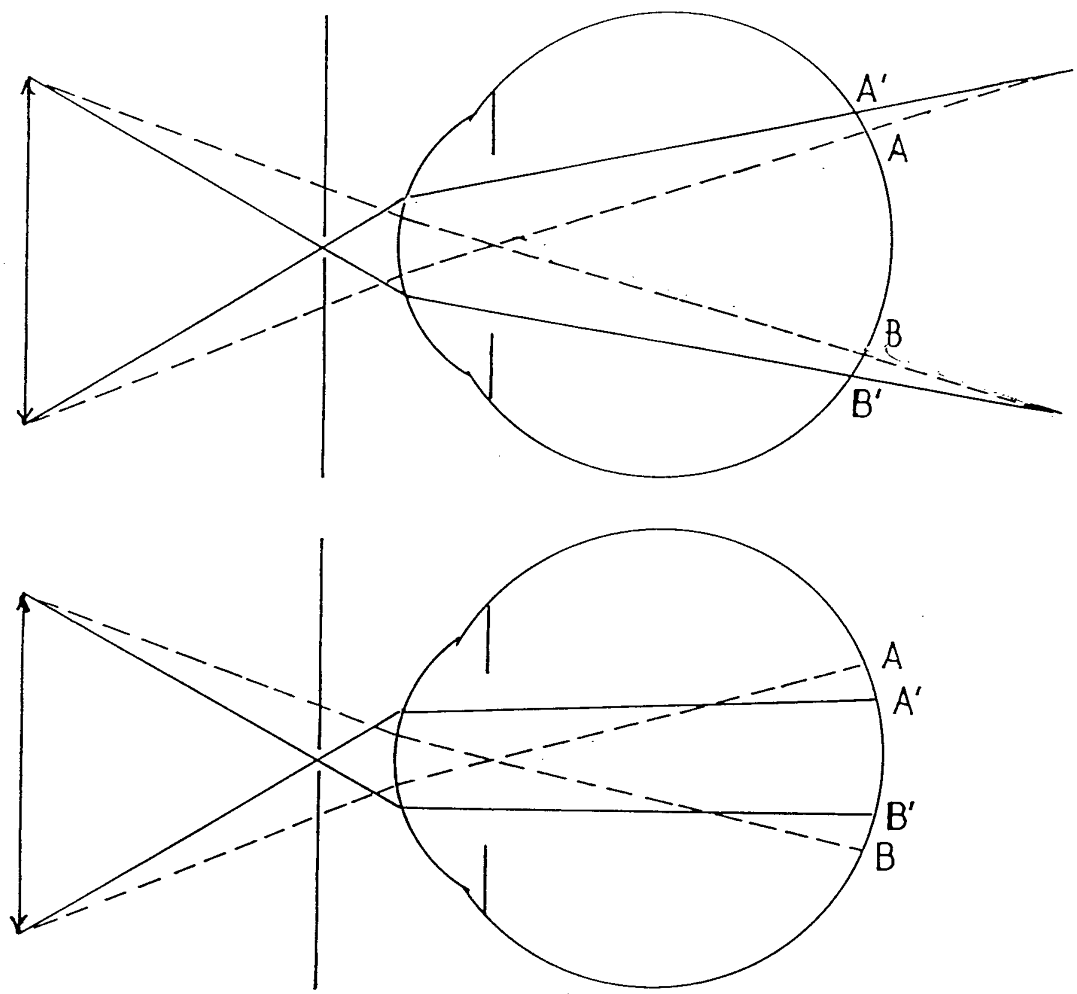

Fig.4. Effect of a small artificial pupil placed in front of the eye on the apparent size of an object when accommodation is in error. In each case the size AB of the retinal image with the natural pupil is defined by the dashed lines, representing the chief rays passing through the centre of the natural pupil, and the size A'B' of the retinal image with the artificial pupil is defined by the full lines, representing the new chief rays passing through the centre of the artificial pupil (a) Near object, accommodation for greater distance (under-accommodation) object appears larger A'B'>AB (b) Near object, accommodation for closer distance (over-accommodation), object appears smaller A'B'<AB.

A second possible reason why size change effects might be smaller with the artificial pupil is that this restricted the field-of-view as well as affecting the depth-of-focus. Manipulation of the depth cues in a scene is known to affect size and distance judgements. For this reason, a further set of experiments was carried out using a reduction screen as well as an artificial pupil.

Experiment 4: Effects of artificial pupil and reduction in field-of-view

For this study standard and comparison targets were compared under four conditions, all with monocular viewing using the dominant eye.

(i) Normal conditions with natural pupils and no restriction on the field-of-view.

(ii) Natural pupils but with a reduction screen to restrict the field so that only the white standard and comparison targets could be seen against their black backgrounds, with no peripheral objects to give additional distance cues. The black-painted reduction screen contained a 10 by 22 mm aperture, so that when placed at a distance of about 120 mm from the eye the field-of-view was limited to about 5 by 11 degrees.

(iii) 1 mm artificial pupil and otherwise unrestricted visual field.

(iv) 1 mm artificial pupil with the reduction screen.

Two-degree square standard targets were used at nominal distances of 3, 1, 0.5, 0.33, 0.25 and 0.2 m, with the comparison target being kept at a distance of 2 m. Actual distances differed slightly from the nominal distances because of small manufacturing differences between the actual and intended sizes of the square targets. A single subject was employed (Subject LH).

The mean results and their standard deviations (bracketed values) derived from 5 settings for each target and condition are summarised in Table 5 and Fig.5.

Table 5: Side length (degrees) of comparison target at 2 m required to match the standard two degree targets for the distances and conditions indicated. Subject LH.

Target distance (m)	1. Normal pupil	2. Normal pupil+ Reduced field	3. Artificial pupil	4.Art.pup.+ Red.Field
3.00	2.17(0.05)	2.04(0.05)	2.14(0.02)	2.04(0.04)
0.994	1.66(0.02)	1.83(0.03)	1.78(0.03)	1.87(0.03)
0.493	1.66(0.06)	1.80(0.04)	1.80(0.02)	1.90(0.04)
0.324	1.71(0.03)	1.73(0.06)	1.92(0.05)	1.93(0.05)
0.250	1.49(0.03)	1.56(0.04)	1.62(0.03)	1.75(0.03)
0.193	1.52(0.06)	1.53(0.06)	1.86(0.03)	1.87(0.03)

While there is some irregularity in the results, the general conclusion is that, for this subject at least, restricting the field-of-view to reduce peripheral cues to distance reduces size changes with both natural and artificial pupils. The smallest changes are found when both an artificial pupil and the reduction screen are used.

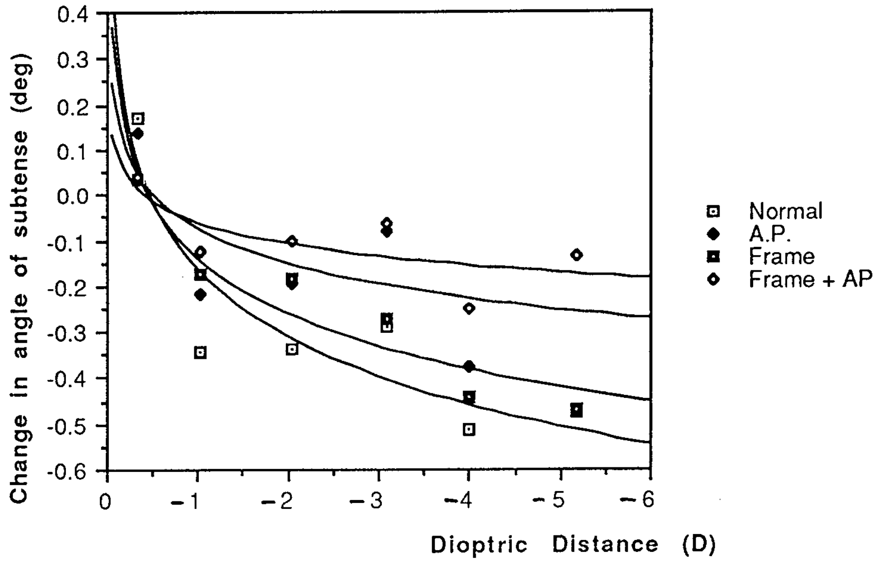

Fig.5. Effect of artificial pupil and restricted field on size estimates of subject LH under monocular conditions. □ Natural pupil, unrestricted field; ■ natural pupil, restricted field; ♦ 1-mm artificial pupil, unrestricted field; ◇ 1-mm pupil, restricted field.

Since only one subject was used it was felt to be desirable to confirm this trend using several subjects. Measurements were therefore repeated with 5 further subjects, using only the standard target at the nominal distance of 0.2 m. The individual and mean results are shown in Table 6 and Fig.6. It can be seen that the trend is very similar for all subjects with one exception, subject G, who in this experiment showed a relatively constant small size reduction under all circumstances.

Table 6: Apparent angular size of two-degree standard target at a viewing distance of 0.2 m, judged by a comparison target at 2 m. The bracketed values with the means are the standard deviations for the 6 subjects.

	Normal pupil	Norm.Pupil+ Red.field	Artificial pupil	Art.pupil.+ red.field
LH*	1.52	1.53	1.86	1.87
G	1.86	1.75	1.79	1.77
S	0.79	1.04	1.39	1.50
N	0.91	1.08	1.20	1.37
O	1.41	1.65	1.61	1.61
E	1.22	1.41	1.79	1.71
Mean	1.29(0.40)	1.41(0.29)	1.61(0.26)	1.64(0.18)

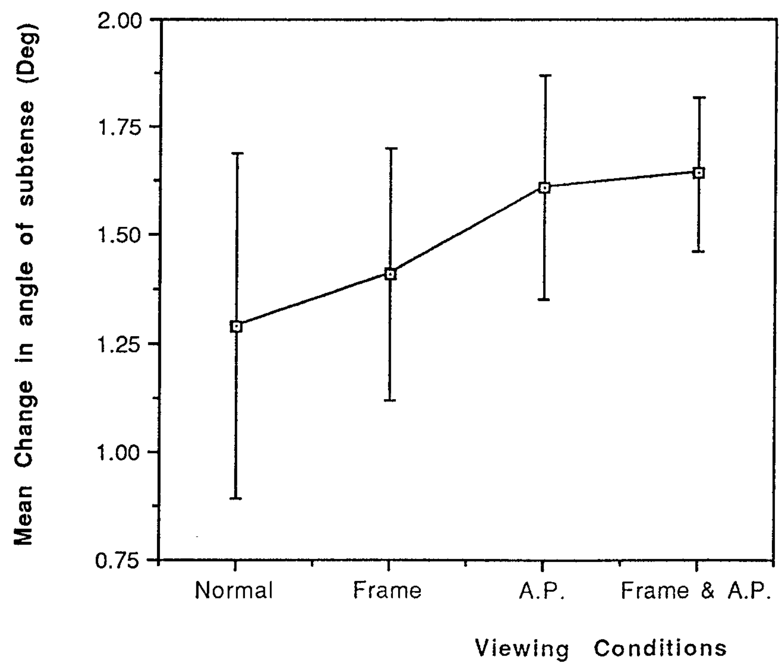

Fig.6. Mean change in apparent size of a 2-degree square standard target at 0.2 m, as judged by 6 subjects, for 4 viewing conditions. "Normal" is for natural pupils and an unrestricted field-of-view; "Frame" is for natural pupils and a restricted field; "A.P." is for a 1-mm artificial pupil and unrestricted field; and "Frame & A.P." is for the artificial pupil with a restricted field.

Experiment 5: After-image comparisons

Although the above experiments and the model eye calculations all support the view that accommodation-dependent changes in the size of the optical image on the retina are unlikely to be responsible for changes in apparent size it was felt to be desirable to carry out a further exploratory experiment using after-images to see if significant size changes could be detected.

A photographic flash unit was masked to leave two clear, vertical bar apertures, with inner edges separated by 2 degrees at the viewing distance used. The subject fixated a point midway between the bars and the flash was fired. The subject's task was then to compare the dimensions of the resultant after-image with those of each of the standard two-degree targets, viewed at their appropriate distances (Fig.7). It would be expected that if retinal image size was invariant with target distance the after-image would always appear to match the dimensions of the targets. On the other hand, marked changes with distance in the sizes of the retinal images of the standard targets would mean that the after-image would only match the standard when both were observed at the same distance.

Matching after-images in this way is difficult and requires some experience, since changes in fixation only affect external targets, not the projected after-image and the after-image periodically fades. Trials suggested, however, that size mismatches of 10% or more should easily be detectable. Subjects were, however, unable to detect any mismatch for any of the targets over the full range of target distances, again supporting the view that large accommodation-dependent changes in the size of the optical image on the retina are unlikely

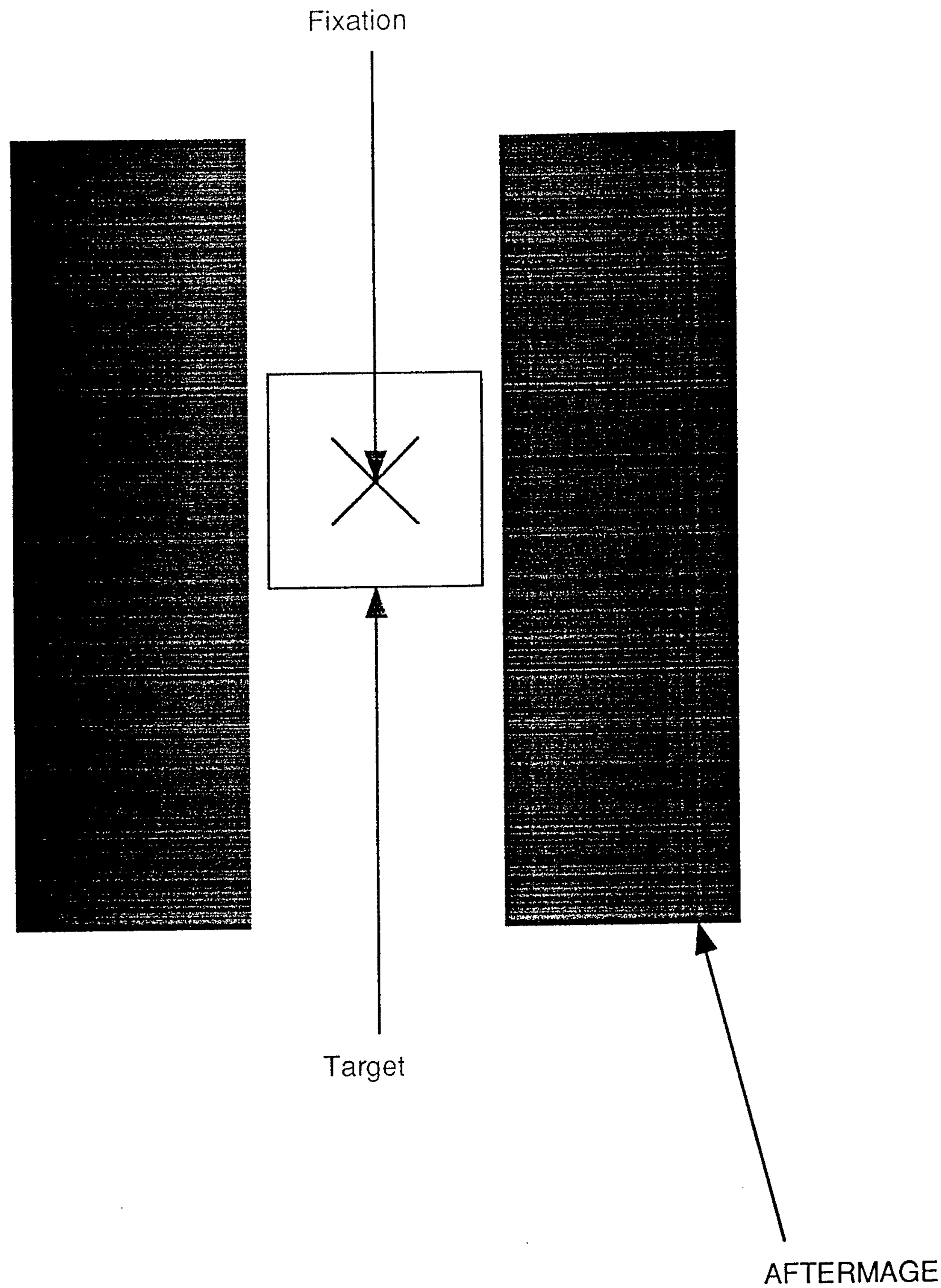

Fig.7. Appearance of standard target and after-image if the retinal image of the standard target is reduced in size due to accommodation.

to occur.

It is worth commenting that this after-image technique also sets constraints on the extent to which retinal stretch caused by accommodation may affect perceived image size. There is evidence (Moses, 1971; Blank and Enoch, 1973; Enoch, 1973, 1974; Hollins, 1974; Miles 1975) that the tractional forces exerted on the retina and choroid by the ciliary body during accommodation may "stretch" the retina so that its anterior margin moves forward with respect to the globe. The effect of such stretch would obviously be to reduce the number of receptors covered by an optical image of constant area, which presumably would result in a smaller perceived image at higher levels of accommodation. With the after-image method, the after-image would expand with the stretched retina, so that the nearer standard targets should appear smaller (assuming that all target images had constant size, irrespective of the target distance). The apparent absence of such an effect therefore sets an observational upper limit of about 10% on the extent of the stretch. In fact, with the current level of development of the after-image method, this upper limit is much greater than the increase of about 1% inferred to occur by Enoch (1973), although it is closer to the stretch of 4% that Hollins (1975) suggested might occur in the central retina.

4. DISCUSSION

We interpret the results of these experiments as indicating, like the model eye calculations, that changes in apparent size as a function of distance are unlikely to be caused by

accommodation-dependent changes in the size of the retinal image. Although we regard our experiments as exploratory rather than definitive they result in the following provisional conclusions for the apparent sizes of objects which all subtend the same angle at the cornea but which differ in distance in the range 0.2 to 3 m:

(i) Apparent size reductions for near objects are greater when binocular, rather than monocular observation is employed.

(ii) Size reductions are greater when the natural pupil (3-4 mm) is used than with a 1mm artificial pupil. Accommodation accuracy is reduced with the small pupil and, correspondingly, less accommodative effort is made to view near targets at vergences greater in magnitude than the tonic accommodation of the subjects.

(iii) Masking the field-of-view to eliminate cues as to the relative distances of the standard and comparison targets reduces changes in apparent size with both natural and artificial pupils.

(iv) Trials with after-images suggest that in these experiments the size of the optical image on the retina of all the standard targets was constant within about ±10%.

It is of interest that these results are, in fact, qualitatively very similar to the classic results of Holway and Boring (1941), although the latter studied effects at somewhat greater distances (about 3 to 30 m). They too found that, in comparison with normal binocular observation, size change effects diminished with monocular vision, use of a small artificial

pupil and reduction of the field-of-view to the targets alone. Both studies imply that, irrespective of observation distance, apparent visual size becomes more closely related to the angular subtense of the object as the viewing conditions become more impoverished.

Although we feel that accommodation-dependent changes in the size of the optical image on the retina are not the source of changes in apparent size, we do not feel that the possibility that innervation to accommodation (and convergence) being a factor in size judgement can be ruled out (see, e.g., Holst and Mittelstadt, 1950; Richards, 1967; Marg and Adams, 1970; Hochberg, 1972; Lockhead and Wolbarsht, 1989). This possibility therefore deserves further consideration, although it is usually suggested that in humans accommodative effort is of little value as a distance cue (Heinemann et al., 1959; Kunnapas, 1968). The work of Leibowitz and his colleagues (Leibowitz and Moore, 1966; Harvey and Leibowitz, 1967) appears to support this suggestion (together with the probable involvement of convergence) although the use by these authors of lenses to stimulate accommodation introduces spectacle magnification which somewhat enhances the effects observed.

It may be commented that anecdotal evidence suggests that changes in apparent size are not necessarily dependent on the presence of active accommodation, since presbyopes also experience the moon illusion (Lockhead and Wolbarsht, 1989; Kaufmann and Rock, 1989).

At the present time, it would appear that the results of apparent size experiments of the present type are most simply explained in terms of a shift from a regime in a cue-rich environment in which size-constancy plays a major role to judgement based purely on

angular subtense when cues to distance are minimised (Holway and Borish, 1941). Table 6 compares the mean experimental results obtained with binocular vision, natural pupils and unrestricted field which collectively give numerous cues to object distance (i.e. Experiment 1) with those which would be predicted on the basis of size constancy, i.e when the subjects were assumed to effectively visualise all the targets as being at the same 2m distance as the comparison target.

Table 6: Apparent subtenses (degrees) based on size-constancy compared with the mean results found in experiment 1.

Distance of standard target (m)	Apparent subtense at 2 m predicted by size constancy	Mean observed subtense (Experiment 1)
3.0	3.00	2.66
1.0	1.00	1.21
0.33	0.33	0.75
0.20	0.20	0.53

Note that although the subjects were not instructed to envisage the standard targets as they would appear if placed at 2 m, but simply to match their apparent size with the comparison target, their results suggest a strong role for size constancy. It seems reasonable to suppose that when conditions do not allow an estimate of the distance of the standard target's distance to be made, judgements become dominated by the true angular subtense of the targets.

It is of interest that both size and shape constancy (e.g.Coren and Ward, 1989, Ch.14) tend to break down in situations where contextual or depth information is meagre. It seems reasonable to assume that such constancies play a role in the judgement of pilots and that the poorer contextual and depth cues provided by the limited resolution and field of night-vision

goggles or other indirect imagery might cause problems for pilots (Brickner, 1989; Hart and Brickner, 1989; Foyle and Kaiser, 1991). It may also be, as suggested in the Interim Report, that "phenomenal regression to the real object" (e.g.Thouless, 1931a,b; Brunswik, 1944; Forgus, 1966; Stavrianos, 1945) plays some role in faulty judgements of size and distance.

To summarise, we remain unconvinced by the argument that errors in size judgement related to the physical dimensions of the associated optical images on the retina. They are much more likely to be perceptual in origin.

5. SUGGESTIONS FOR FUTURE WORK

It should again be emphasised that the present experimental study was of an exploratory nature, designed to validate the general experimental approach and to determine at least some of the major factors influencing the size judgements. It is desirable that the experiments be repeated with larger numbers of subjects, a greater range of standard targets, improved monitoring of accommodation and some improvements in the matching techniques. In particular, the relatively slow speed of the available computer made adjustments of the comparison target a rather slow procedure, leading to unnecessary fatigue and boredom for the subjects. For certain experiments a forced-choice method rather than the method of adjustment would be preferable and some control studies using cycloplegia or presbyopic

subjects would be useful. Further studies would concern the effects of convergence, luminance and colour.

Most of these suggestions were covered in the research proposal submitted on 18th March 1994.

The after-image technique would appear to be potentially useful as a way of separating optical image size changes from perceptual changes. The present method is almost certainly non-optimal both in terms of the available flash intensity and in the flash geometry used, so that it should be possible to significantly improve the accuracy of after-image/target comparisons. One obvious and attractive experiment is to match the comparison target against an after-image, the comparison target being placed at varying distances. Measurements with an artificial pupil at various distances in front of the eye (cf Biersdorf and Baird, 1966) would be useful since they could be compared with theoretical predictions (Marsh and Temme, 1990; Smith et al., 1992) to validate the models concerned.

Lastly we suggest that an exploration of possible accommodation errors when viewing collimated imagery (Randle et al., 1980; Hull et al., 1982; Iavecchia et al., 1988) would be of interest not primarily from the point of view of possible size changes in the retinal image but rather because errors of focus may lead to failure to acquire high spatial frequency information. It may be that some of the suggested accommodation errors are caused by the competing cues offered by peripheral stimuli such as lens or other mounts, rather than by the influence of tonic accommodation.

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